UDC 658.5.011

https://doi.org/10.29202/nvngu/2019-6/17

E. I. Kabanov, Cand. Sc. (Tech.), orcid.org/0000-0001-7580-9099,
G. I. Korshunov, Dr. Sc. (Tech.), Prof., orcid.org/0000-0001-9832-4123,
E. B. Gridina, Cand. Sc. (Tech.), Assoc. Prof., orcid.org/0000-0002-7265-1115

Saint Petersburg Mining University, St. Petersburg, Russian Federation, e-mail: kabanov_ei@pers.spmi.ru

ALGORITHMIC PROVISIONS FOR DATA PROCESSING UNDER SPATIAL ANALYSIS OF RISK OF ACCIDENTS AT HAZARDOUS PRODUCTION FACILITIES

Purpose. Rationale of priority areas in the field of hazard analysis at hazardous production facilities (HPF) and the development of a method that allows for spatial analysis of the risk of accidents at a high level of detail.

Methodology. The authors proposed a method for processing heterogeneous information in order to identify hazardous areas for accidents, based on systematization and processing of source data using expert systems.

Findings. Using the example of spatial analysis of risk of explosion of methane-air mixture in the working area of a coal mine, the possibility of practical implementation of the proposed method was demonstrated. For this purpose, an expert system was used, which was formed on the basis of fuzzy logic inference algorithms in MATLAB Fuzzy Logic Toolbox environment, and further point interpolation was performed using the Golden Software Surfer.

Originality. Based on the model of expert system of a fuzzy logical output, relationships have been established between a numerical indicator of the risk of an accident – an explosion of a methane-air mixture, and indicators of mining, geological, mining, subjective, and organizational risk factors. The expediency of the development of separate expert systems for the analysis of individual sources of hazards in order to create a single component object environment for the implementation of comprehensive analysis of safety of HPF is substantiated.

Practical value. The work presents the rationale for the universality of the chosen methodological approach, which allows adapting expert systems for analyzing various hazards on HPF in various industries. The obtained results can be used for the timely and targeted implementation of preventive protective measures, which will be the practical use of the principles of the risk-based approach (RBA) in ensuring the safety of HPF.

Keywords: *accident, unclear logical conclusion, hazardous production facility, labor protection, industrial safety, spatial risk analysis, point interpolation, expert system*

Introduction. The systematic occurrence of accidents at hazardous production facilities (HPF) requires introduction of qualitatively new approaches for ensuring industrial and environmental safety [1, 2]. These approaches should be based on principles of timely targeted implementation of preventive protective measures, based on systemic hazard analysis, periodic assessment and forecast of risk indicators [3, 4]. Moreover, high practical level of interest is directed to high-detail risk analysis which allows for localization of hazards and hazardous areas.

Remote monitoring systems at production environment have significant potential for the development of RBA, since the provided operational information about hazards, their localization and associated risks can be used to make effective management decisions. The implementation of the RBA will allow timely detection of "bottlenecks" in the system for ensuring industrial and environmental safety HPF. In turn, this requires the availability of appropriate algorithmic support for spatial risk analysis, taking into account the results of monitoring of hazards and possible scenarios leading to the accident at the HPF.

Unsolved aspects of the problem. The analysis of methodological support showed that there were separate approaches to the assessment of the risk of accidents at HPF taking into account their specificity [5, 6], based on statistical, probabilistic and expert methods of analysis. Nonetheless, the presence of a wide range of heterogeneous risk factors in combination with the amount of information available for analysis imposes restrictions on the use of individual methods in comprehensive hazard assessment [7, 8]. Overcoming the mentioned limitations can be achieved by using expert systems with hierarchical structure, which allow aggregating information in a formalized form and calculating risk indicators using established algorithms. Then, for analyzing various hazards, it is advisable to use separate expert systems, including those that exist now [9, 10]. Therefore, the solution of the problem of methodological support for spatial analysis of the risk of various accidents at the HPF can be achieved using the universal approach [11], which is the basis for developing complex risk indicators when combining separate expert systems, and allowing us:

- to calculate, evaluate and forecast numerical indicators of risks, taking into account the specifics of HPF on the basis of heterogeneous information (deterministic, statistical, interval, linguistic);
- to take into account a complex of heterogeneous factors that allow performing spatial analysis of risks at high level of detail;

- to analyze possible scenarios and forecast the distribution of hazardous areas in case of an accident at HPF;

- to provide the ability to automate the process when using remote monitoring sources of hazards.

Therefore, the use of a set of specialized expert systems allows us to perform a spatial analysis of risks of accidents at HPF at a high level of detail, which implies the accumulation of a significant amount of source data. The structuring of initial information and formation of array of data for further processing in expert systems can be performed in accordance with the method presented below.

Purpose. Rationale of the priority directions in the field of hazard analysis at HPF and the development of a method that allows performing spatial analysis of the risk of accidents at a high level of detail.

Materials and methods. The main task in the spatial analysis of accident risk at the HPF is the identification and delineation of hazardous areas, which can be performed during the formation of the fields of spatial distribution of risk indicators. This distinction is made on the basis of an analysis of the results of interpolation of risk index, the values of which are determined at various points in the studied space of the production environment of the HPF. The algorithm for processing and analyzing data is presented in Fig. 1, and its main stages are:

1. Collecting source data at m points of the production environment of HPF and forming an array of data – M describing the values of the indicators *f of the* analyzed complex of n accident risk factors – $f_{i,j}$, (where i is the point index of the production environment of HPF, $i = 1.2, \dots, m$; j is the factor index, $j = 1, 2, \dots, n$), including:

- values of factors characterizing the level of potential danger and established in accordance with the actual data obtained during the operation of HPF (including insitu measurement methods and laboratory tests);

- values of indicators of organizational factors characterizing a degree of compliance with the established safety requirements;

- values of indicators for subjective factors.

2. Choosing the i^{th} point of HPF spatial environment, analyzing an ordered set of risk factors for an accident at a given point $F_i = (f_1, \dots, f_n)$ and determining the risk indicator R at a given point – R_i using an expert system.

3. Repetition of point 2 for all m points of the production environment of HPF.

4. Performing a spatial risk analysis using the grid interpolation method based on the distribution of the indicator R in the analyzed HPF space.

5. Determination of k hazardous areas of HPF, whose risk indicators R_l (where l is the hazardous area index of the working environment of HPF, $l = 1, 2, \dots, k$) exceed the level of acceptable risk R_{tol} (the value of R_{tol} is set at the development stage of the used expert system) according to the formula (1)

$$R_l > R_{tol}. \quad (1)$$

6. Selection of the l^{th} danger zone, determination of an accident scenario prevailing at HPF – S_l by identifying maximal $p_{w(\max)}$ values of parameters among parameters of the internal variables r of the p expert system model w–s levels of the hierarchical structure of the expert system (2) – $p_{w,q}$ (where $w = 1, 2, \dots, z$, z is the number of levels of the hierarchical structure of the expert system, q is the index of the internal variable, $q = 1, 2, \dots, r$)

$$p_{w(\max)} = \max(p_w, q); \quad (2)$$

$$s_l = (p_{1(\max)}, p_{2(\max)}, \dots, p_{z(\max)}). \quad (3)$$

7. Analysis of S_l, l – scenario for the second area and determining the root causes of the accident (3).

Results. The possibility of implementing the method of spatial risk assessment is presented by an example of analysis of the risk of an accident at a HPF – the occurrence of a meth-

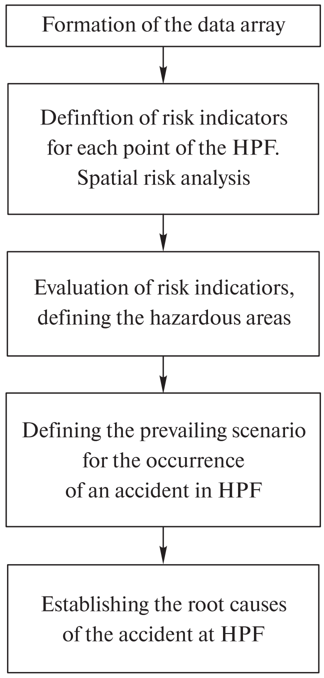

Fig. 1. The main stages of the method of spatial analysis of the risk of an accident at HPF

ane explosion at the mining site of a coal mine. As an expert system, a mathematical model of fuzzy logical output was used, implemented in the MATLAB Fuzzy Logic Toolbox environment. For this, considering the results of statistical analysis, mathematical modeling and expert evaluation, the procedures for the formation of linguistic variables and production rules for fuzzy inference were carried out in order to create a knowledge base with a hierarchical structure [12].

These models are highly adaptable to tasks of classification and risk analysis and are widely used to assess and predict the risk of accidents and occupational risks at HPF [13, 14]. The variables used in algorithms of fuzzy inference as input data allow us to aggregate non-uniform information about risk factors into the knowledge base of the expert system and to give their indicators a universal scale. Based on fuzzy inference procedures, expert systems with hierarchical knowledge base can be developed, which makes an opportunity to analyze various combinations of initiating events [15, 16].

The developed expert system can be used in addition to existing methods for assessing the air-related risk of accidents at coal mine sites [17, 18] and allows generating the following output:

- a numerical indicator of the risk of an explosive methane-air mixture (MAM) (as a result of a decrease in the intensity of ventilation and degassing, the formation of poorly ventilated zones) R_G;

- a numerical indicator of risk of high-temperature impulse (as a result of spontaneous combustion, friction, the use of electrical equipment and open fire) – R_T;

- a numerical indicator for risk of methane explosion – R_E;

- numerical indicators for internal variables that allow the analysis of possible scenarios and causes of adverse events – $p_{w,q}$.

To perform a spatial risk analysis at a high level of detail, an array of data was generated based on the results of survey of the production environment of coal mine production unit with the definition of indicators R_G, R_T and R_E for each analyzed point of production environment of HPF. In the future, the grid interpolation of data using the "Inverse Distance to a Power" and "Kriging" methods in the Golden Software Surfer 9 system was performed. The resulting spatial distribution of risk R_E is shown in Fig. 2.

The obtained results characterize the risk levels during operation of the mine in normal mode. At a later stage, in order to determine sensitivity of the developed model to risk factors, a numerical simulation of a pre-emergency situation was done according to one of the typical scenarios of an MAM explosion at a coal mine: a decrease in the ventilation intensity of the mining site with high methane concentration and exploitation of the mining equipment with impaired explosion-proof performance. Spatial risk analysis results R_G and R_T performed by grid data interpolation are shown in Figs. 3 and 4.

Since the simulated events are of a stochastic nature and are independent, the risk of an accident – the explosion of MAM R_E can be calculated in accordance with the probability multiplication theorem using the formula

$$R_E = R_G \cdot R_T. \quad (4)$$

Expression (4) is valid under assumption that the numerical risk indicator is considered as a measure of possibility of the event being analyzed. The possibility of presenting a numerical risk indicator as a quantitative indicator of probability can be established depending on the objectives of the risk analysis in each case.

The resulting spatial distribution of risk indicator R_E is presented in Fig. 5.

As output data when using the model, intermediate indicators defined at different levels of the expert system knowledge base hierarchy were also obtained, which made it possible

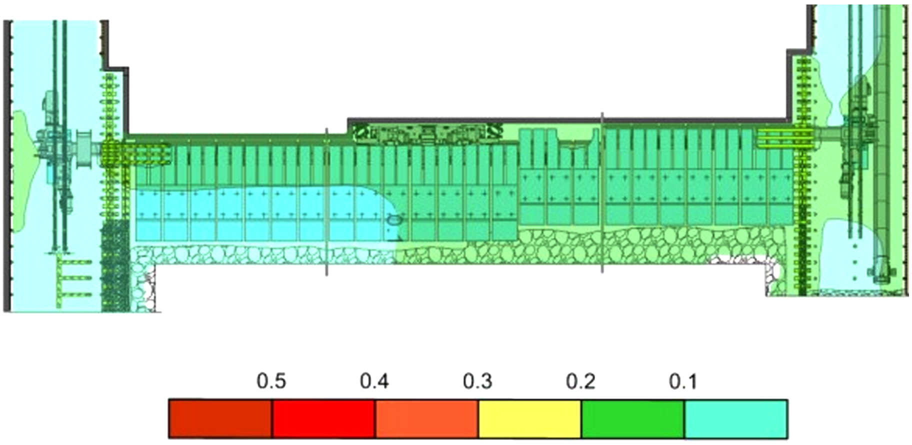

Fig. 2. Spatial distribution of risk of occurrence of MAM explosion in working area of a coal mine

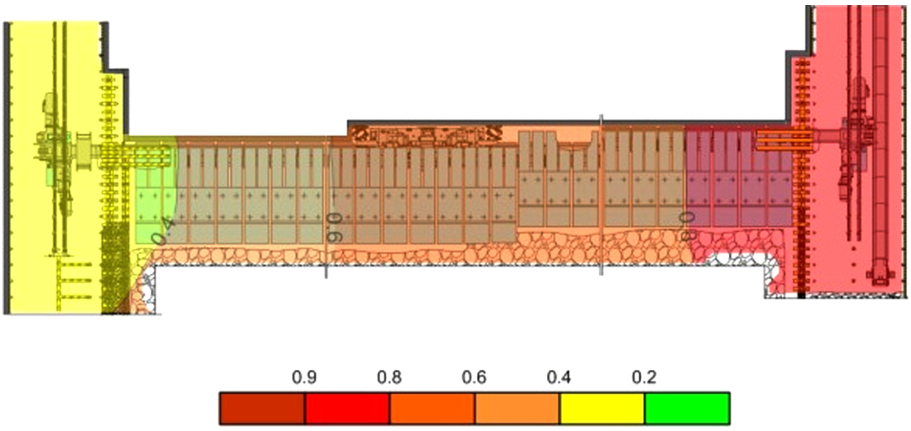

Fig. 3. Spatial distribution of the risk of MAM explosive R_G when modeling conditions for reducing intensity of ventilating the site

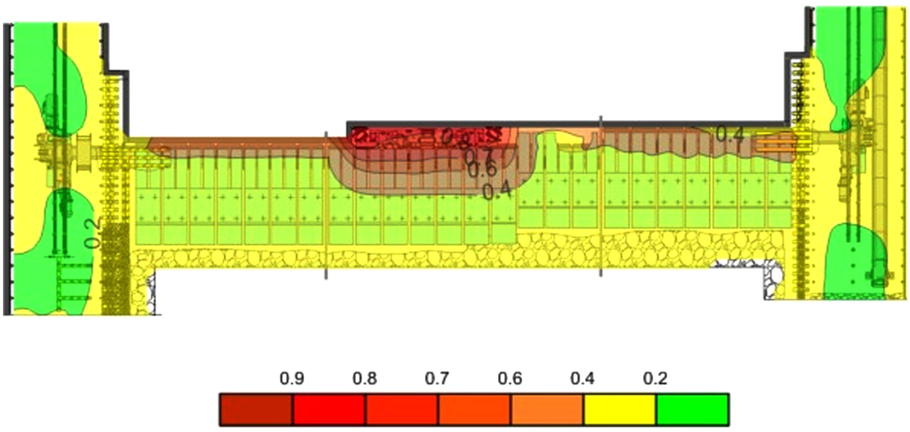

Fig. 4. Spatial distribution of the risk of a source of high-temperature impulse R_T when modeling operating conditions of electrical equipment of a mining combine with impaired explosion-proof design

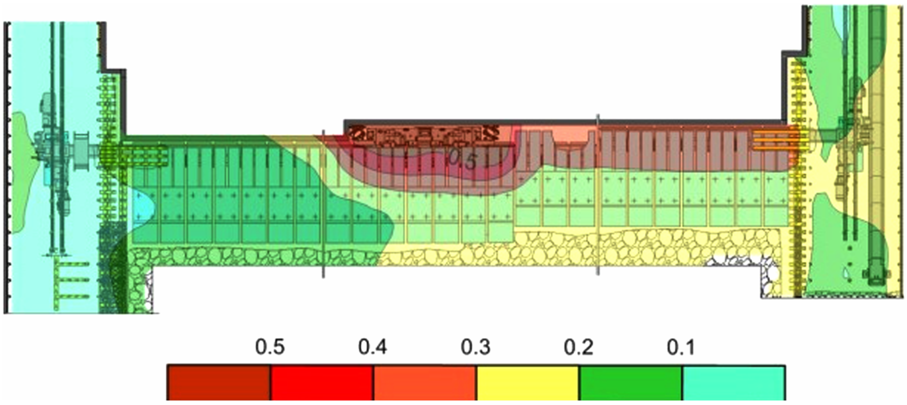

Fig. 5. Spatial distribution of MAM explosion risk R_E in the numerical simulation of the accident conditions

to describe scenario of the simulated "MAM Explosion" accident with the establishment of root causes:

a) formation of an explosive environment → violation of procedures of ventilation of workings → formation of areas with insufficient airing → low level of air provision in working (root cause);

b) formation of high-temperature source of initiation → the emergence of an electric spark / arc discharge → failure to take measures to ensure the explosion safety of electrical equipment → a low level of electrical equipment compliance with the requirements established by the operational documentation of the mine and manufacturer (root cause).

Conclusions. The data obtained during the spatial risk analysis using the proposed algorithm facilitates localization of hazard sources at a high level of detail, taking into account the combined effects of risk factors. At the same time, numerical information on risk indicators allows ranking the zones by hazard level taking into account various scenarios of an accident at HPF.

The obtained results can be used for timely and targeted implementation of preventive protective measures, which indicates the implementation of RBA principles while ensuring the safety of HPF.

The high effectiveness of the safety activities for HPF can be achieved by promptly making timely management decisions on the implementation of protective measures, which is possible while ensuring a high level of automation of the data collection processes for performing spatial analysis of risks. This testifies to the high relevance of application of the developed data processing method within the framework of remote monitoring systems of hazards in real time.

On the example of the considered mathematical model, the expediency of using expert systems based on fuzzy logic is shown when conducting a spatial analysis of the risk of accidents at HPF with a high level of detail. It also displayed the possibility of implementing the principles of a priori analysis of working environment, conducting comprehensive risk assessment based on heterogeneous data, including taking into account possible deviations from the norms and rules of safety.

The universality of the selected approach makes it possible to adapt expert systems for analyzing various sources of hazard at HPF in various industries. Wherein, it seems expedient to develop separate expert systems for analyzing individual sources of hazards, which can be combined into a single component object environment for the implementation of comprehensive safety analysis of HPF.

References.

1. Barkan, M. Sh., & Kornev, A. V. (2018). Development of New Technological Solutions for Recovery of Heavy Nonferrous Metals fromTechnogenic Waste of Electroplating Plants and Sludge of Water Treatment Systems. *Eastern-European Journal of Enterprise Technologies*, *2*(10-92), 17-24.

2. Filimonov, V. A., & Gorina, L. N. (2019). Development of an Occupational Safety Management System. *Journal of Mining Institute*, *235*, 113-122.

3. Kireeva, E. V., & Kireev, M. S. (2017). Risk-oriented Approach to Design of the Industrial Safety System: Problems. *Solutions. International Journal of Applied Engineering Research*, *12*(16), 5463-5471.

4. Voronov, S. P., Matushin, A. V., & Shlepenev, M. M. (2016). Application of risk-based approach in the state fire supervision activities. *Bulletin of St. Petersburg State Fire Service University of EMERCOM of Russia*, (1), 130-140.

5. Kabir, S., & Popadopoulos, Y. (2019). Applications of Bayesian Networks and Petri Nets in Safety, Reliability, and Risk Assessments: A Review. *Safety Science*, *115*, 154-175.

6. Korshunov, G. I., Kazanin, O. I., & Rudakov, M. L. (2017). Development of Accidents Risk Assessment Techniques for Coal Mines Taking into Account Specific Conditions. *Mining Informational and Analytical Bulletin*, *4*(5-1), 374-382.

7. Shabtai, I., & Tsah, E. (2016). A Statistical Model for Dynamic Safety Risk Control on Construction Sites. *Automation in Construction*, *63*, 66-78.

8. Sobral, J., & Soares, C. G. (2019). Assessment of the Adequacy of Safety Barriers to Hazards. *Safety Science*, *114*, 40-48.

9. Myasnikov, S. V., Korshunov, G. I., & Kabanov, E. I. (2018). Method of Complex Estimation and Forecast of Professional Risk of Injury of Coal Mines Personnel due to Methane and Dust Explosions. *Occupational Safety in Industry*, (5), 60-65.

10. Sarbayev, M., Yang, M., & Wang, H. (2019). Risk Assessment of Process Systems by Mapping Fault Tree into Artificial Neural Network. *Journal of Loss Prevention in the Process Industries*, *60*, 203-212.

11. Yazdi, M., Hafezi, P., & Abbasi, R. (2019). A Methodology for Enhancing the Reliability of Expert System Applications in Probabilistic Risk Assessment. *Journal of Loss Prevention in the Process Industries*, *58*, 51-59.

12. Kabanov, E. I. (2019). Expert System for Complex Express-Assessment and Forecast of Accidents Risk and Professional Risks on Coal Mines. *Mining Informational and Analytical Bulletin*, (4), 78-86.

13. Koulinas, G. K., Marhavilas, P. K., & Demesouka, O. E. (2019). Risk Analysis and Assessment in the Worksites Using the Fuzzy-Analytical Hierarchy Process and a Quantitative Technique – A Case Study for the Greek Construction Sector. *Safety Science*, *112*, 96-104.

14. Nourian, R., Mousavi, S. M., & Raissi, S. (2019). A Fuzzy Expert System for Mitigation of Risks and Effective Control of Gas Pressure Reduction Stations with a Real Application. *Journal of Loss Prevention in the Process Industries*, *59*, 77-90.

15. Urbina, A. G., & Aoyama, A. (2017). Measuring the Benefit of Investing in Pipeline Safety Using Fuzzy Risk Assessment. *Journal of Loss Prevention in the Process Industries*, *45*, 116-132.

16. Qiu, S., Sallak, M., Schon, W., & Mingac, H. X. G. (2018). A Valuation-Based System Approach for Risk Assessment of Belief Rule-Based Expert Systems. *Information Science*, *466*, 323-336.
17. Balovcev, S. V. (2015). Assessment of the Accidents Risk of the Excavation Sites of Coal Mines. *Gorniy Zhurnal*, (5), 91-93.
18. Smirnyakov, V. V., & Fien, N. M. (2018). Justification of a Methodical Approach of Aerologic Evaluation of Methane Hazard in Development Workings at Mines of Vietnam. *Journal of Mining Institute*, *230*, 197-203.

Алгоритмічне забезпечення для обробки даних при просторовому аналізі ризику аварій на небезпечних виробничих об`єктах

Є. І. Кабанов, Г. І. Коршунов, О. Б. Грідіна
Санкт-Петербурзький гірничий університет, м. Санкт-Петербург, Російська Федерація, e-mail: kabanov_ei@pers.spmi.ru

Мета. Обґрунтування пріоритетних напрямів в області аналізу небезпек на небезпечних виробничих об`єктах (НВО) та розробка методу, що дозволяє виконувати просторовий аналіз ризику аварій на високому рівні деталізації.

Методика. Авторами запропоновано метод обробки неоднорідної інформації з метою визначення небезпечних зон під час аварій, заснований на систематизації та обробці вихідних даних з використанням експертних систем.

Результати. На прикладі просторового аналізу ризику вибуху метаноповітряної суміші на добувних ділянках вугільної шахти була показана можливість практичної реалізації запропонованого способу. Для цього була використана експертна система, сформована на основі алгоритмів нечіткого логічного висновку в середовищі MATLAB Fuzzy Logic Toolbox, і проведена подальша точкова інтерполяція з використанням програмного забезпечення Golden Software Surfer.

Наукова новизна. На основі моделі експертної системи нечіткого логічного висновку встановлені зв`язки між чисельним показником ризику аварії – вибуху метаноповітряної суміші, і показниками гірничо-геологічних, гірничотехнічних, суб`єктивних і організаційних чинників ризику. Обґрунтована доцільність розробки відокремлених експертних систем для аналізу окремих джерел небезпек з метою створення єдиного компонентного об'єктного середовища для реалізації комплексного аналізу безпеки НВО.

Практична значимість. У роботі обґрунтована універсальність обраного методичного підходу, що дозволяє адаптувати експертні системи для аналізу різних джерел небезпеки на НВО різних галузей. Отримані результати можуть бути використані для своєчасної та адресної реалізації превентивних захисних заходів, що є практичним використанням принципів ризик-орієнтованого підходу (РОП) при забезпеченні безпеки НВО.

Ключові слова: *аварія, нечіткий логічний висновок, небезпечний виробничий об'єкт, охорона праці, виробнича безпека, просторовий аналіз ризику, точкова інтерполяція, експертна система*

Алгоритмическое обеспечение для обработки данных при пространственном анализе риска аварий на опасных производственных объектах

Е. И. Кабанов, Г. И. Коршунов, Е. Б. Гридина
Санкт-Петербургский горный университет, г. Санкт-Петербург, Российская Федерация, e-mail: kabanov_ei@pers.spmi.ru

Цель. Обоснование приоритетных направлений в области анализа опасностей на опасных производственных объектах (ОПО) и разработка метода, позволяющего производить пространственный анализ риска аварий на высоком уровне детализации.

Методика. Авторами предложен метод обработки неоднородной информации в целях определения опасных зон при авариях, основанный на систематизации и обработке исходных данных с использованием экспертных систем.

Результаты. На примере пространственного анализа риска взрыва метановоздушной смеси на добычном участке угольной шахты была показана возможность практической реализации предложенного способа. Для этого была использована экспертная система, сформированная на основе алгоритмов нечеткого логического вывода в среде MATLAB Fuzzy Logic Toolbox, и произведена дальнейшая точечная интерполяция с использованием программного обеспечения Golden Software Surfer.

Научная новизна. На основе модели экспертной системы нечеткого логического вывода установлены связи между численным показателем риска аварии – взрыва метановоздушной смеси, и показателями горно-геологических, горнотехнических, субъективных и организационных факторов риска. Обоснована целесообразность разработки обособленных экспертных систем для анализа отдельных источников опасностей в целях создания единой компонентной объектной среды для реализации комплексного анализа безопасности ОПО.

Практическая значимость. В работе приведено обоснование универсальности выбранного методического подхода, позволяющего адаптировать экспертные системы для анализа различных источников опасности на ОПО различных отраслей. Полученные результаты могут быть использованы для своевременной и адресной реализации превентивных защитных мероприятий, что является практическим использованием принципов риск-ориентированного подхода (РОП) при обеспечении безопасности ОПО.

Ключевые слова: *авария, нечеткий логический вывод, опасный производственный объект, охрана труда, производственная безопасность, пространственный анализ риска, точечная интерполяция, экспертная система*

Recommended for publication by I. M. Ihnatenko, Doctor of Geological Sciences. The manuscript was submitted 20.02.19.